

## CLAIMS

We claim:

1. A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a characteristic laser pulse width, said method comprising the steps of:
  - a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said characteristic laser pulse width; and
  - b. focusing said beam to a point above the surface of the material.
2. The method according to claim 1 wherein the material is a metal, the pulse width is 10 to 10,000 femtoseconds, and the beam has an energy of 1 nanojoule to 1 microjoule.
3. The method according to claim 1 wherein the spot size is varied within a range of 1 to 100 microns by changing the f number of the laser beam.
4. The method according to claim 1 wherein the spot size is varied within a range of 1 to 100 microns by varying the target position.
5. The method according to claim 1 wherein the material is transparent to radiation emitted by the laser and the pulse width is 10 to 10,000 femtoseconds, the beam has an energy of 10 nanojoules to 1 millijoule.
6. The method according to claim 1 wherein the material is biological tissue, the pulse width is 10 to 10,000 femtoseconds and the beam has an energy of 10 nanojoules to 1 millijoule.

7. A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a predetermined laser pulse width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said predetermined laser pulse width obtained by determining the ablation (LIB) threshold of the material as a function of pulse width and by determining where the ablation (LIB) threshold function is no longer proportional to the square root of pulse width; and

b. focusing said beam to a point above the surface of the material.

8. The method according to claim 1 wherein the laser beam has an energy in a range of 10 nanojoules to 1 millijoule.

9. The method according to claim 1 wherein the laser beam has a fluence in a range of 100 millijoules per square centimeter to 100 joules per square centimeter.

10. The method according to claim 1 wherein the laser beam defines a spot in or on the material and the LIB causes ablation of an area having a size smaller than the area of the spot.

11. The method according to claim 1 wherein the laser beam has a wavelength in a range of 200 nanometers to 2 microns.

12. The method according to claim 1 wherein the pulse width is in a range of a few picoseconds to femtoseconds.

13. The method according to claim 1 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.

14. The method according to claim 1 wherein the breakdown includes plasma formation.

15. The method according to claim 1 wherein the breakdown includes disintegration.

16. The method according to claim 1 wherein the breakdown includes ablation.

17. The method according to claim 1 wherein the breakdown includes vaporization.

18. The method according to claim 1 wherein the spot size is varied by flexible diaphragm to a range of 1 to 100 microns.

19. The method according to claim 1 wherein a mask is placed in the path of the beam to block a portion of the beam to cause the beam to assume a desired geometric configuration.

20. The method according to claim 1 wherein the laser operating mode is non-TEM<sub>00</sub>.

21. The method according to claim 1 wherein the laser beam defines a spot and has a lateral gaussian profile characterized in that fluence at or near the center of the beam spot is greater than the threshold fluence whereby the laser induced breakdown is ablation of an area within the spot.

22. The method according claim 22 wherein the spot size is a diffraction limited spot size providing an ablation cavity having a diameter less than the fundamental wavelength size.

23. The method according to claim 1 wherein the characteristic pulse width is obtained by determining the ablation (LIB) threshold of the material as a function of pulse width and

determining where the ablation (LIB) threshold function is no longer proportional to the square root of pulse width.

24. A method for laser induced breakdown of a material which comprises:

- a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than a pulse width value corresponding to a change in slope of a curve of fluence breakdown threshold (Fth) as a function of laser pulse width (T), said change occurring at a point between first and second portions of said curve, said first portion spanning a range of relatively long pulse width where Fth varies with the square root of pulse width ( $T^{1/2}$ ) and said second portion spanning a range of short pulse width relative to said first portion with a Fth versus T slope which differs from that of said first portion; and
- b. focusing said one or more pulses of said beam to a point at or beneath the surface of the material.

25. The method according to claim 24 and further including:

- a. identifying a pulse width start point;
- b. focusing the laser beam initial start point at or beneath the surface of the material; and
- c. scanning said beam along a predetermined path in a transverse direction.

26. The method according to claim 24 and further including:

- a. identifying a pulse width start point;
- b. focusing the laser beam initial start point above the surface of the material; and
- c. scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the Rayleigh range.

27. The method according to claim 24 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.

28. The method according to claim 24 wherein the breakdown includes plasma formation.

29. The method according to claim 24 wherein the breakdown includes disintegration.

30. The method according to claim 24 wherein the breakdown includes ablation.

31. The method according to claim 24 wherein the breakdown includes vaporization.

32. The method according to any one of claims 1, 2, 5 or 24 wherein said beam is obtained by chirped-pulse amplification (CPA) means comprising means for generating a short optical pulse having a predetermined duration; means for stretching such optical pulse in time; means for amplifying such time-stretched optical pulse including solid state amplifying media; and means for recompressing such amplified pulse to its original duration.

33. A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a predetermined laser pulse width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said predetermined laser pulse width; and

b. focusing said beam to a point above the surface of the material so that the laser beam defines a spot and has a lateral gaussian profile characterized in that fluence at or near the center of the beam spot is greater than the threshold fluence whereby the laser induced breakdown is ablation of an area within the spot.

34. The method according to claim 33 wherein the spot size is a diffraction limited spot size providing an ablation cavity having a diameter less than the fundamental wavelength size.

35 A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a predetermined laser pulse width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said predetermined laser pulse width; and

b. focusing said beam to a point above the surface of the material which is biological tissue, the pulse width is 10 to 10,000 femtoseconds and the beam has an energy of 10 nanojoules to 1 millijoule.

36. A method for laser Induced breakdown (LIB) of a material by plasma formation with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a distinct change in slope at a characteristic laser pulse width, said method comprising the steps of:

a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said characteristic laser pulse width, said characteristic pulse width being defined by the ablation (LIB) threshold of the material as a function of pulse width where the ablation (LIB) threshold function is no longer proportional to the square root of pulse width; and

b. focusing said beam to a point above the surface of the material and inducing breakdown by plasma formation in the material.

37. A method for laser induced breakdown of a material which comprises:

- a. determining, for a selected material, a characteristic curve of fluence breakdown threshold ( $F_{th}$ ) as a function of laser pulse width;
- b. identifying a pulse width value on said curve corresponding to a rapid and distinct change in slope of said  $F_{th}$  versus pulse width curve characteristic of said material;
- c. generating a beam of one or more laser pulses, said having a pulse width at or below said pulse width value corresponding to said distinct change in slope; and
- d. focusing said one or more pulses of said beam to a point above the surface of the material.

38. The method according to claim 37 and further including:

- a. identifying a pulse width start point;
- b. focusing the laser beam initial start point at or beneath the surface of the material; and
- c. scanning said beam along a predetermined path in a transverse direction.

39. The method according to claim 37 and further including:

- a. identifying a pulse width start point;
- b. focusing the laser beam initial start point above the surface of the material; and
- c. scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the Rayleigh range.

40. The method according to claim 37 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.

41. The method according to claim 37 wherein the breakdown includes plasma formation.

42. The method according to claim 37 wherein the breakdown includes disintegration.

43. The method according to claim 37 wherein the breakdown include ablation.

44. The method according to claim 37 wherein breakdown includes vaporization.

45. The method according to any one of claims 35, or 37 wherein said beam is obtained by chirped-pulse amplification (CPA) means comprising means for generating a short optical pulse having a predetermined duration; means for stretching such optical pulse in time; means for amplifying such time-stretched optical pulse including solid state amplifying media; and means for recompressing such amplified pulse to its original duration.

46. A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a characteristic laser pulse width, said method comprising the steps of:

a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said characteristic laser pulse width; and

b. focusing said beam to a point at or beneath the surface of the material.

47. The method according to claim 46 wherein the material is a metal, the pulse width is 10 to 10,000 femtoseconds, and the beam has an energy of 1 nanojoule to 1 microjoule.

48. The method according to claim 46 wherein the spot size is varied within a range of 1 to 100 microns by changing the f number of the laser beam.



49. The method according to claim 46 wherein the spot size is varied within a range of 1 to 100 microns by varying the target position.

50. The method according to claim 46 wherein the material is transparent to radiation emitted by the laser and the pulse width is 10 to 10,000 femtoseconds, the beam has an energy of 10 nanojoules to 1 millijoule.

51. The method according to claim 46 wherein the material is biological tissue, the pulse width is 10 to 10,000 femtoseconds and the beam has an energy of 10 nanojoules to 1 millijoule.

52. A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a predetermined laser pulse width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said predetermined laser pulse width obtained by determining the ablation (LIB) threshold of the material as a function of pulse width and by determining where the ablation (LIB) threshold function is no longer proportional to the square root of pulse width; and

b. focusing said beam to a region of least confusion above the surface of the material.

53. The method according to claim 46 wherein the laser beam has an energy in a range of 10 nanojoules to 1 millijoule.

54. The method according to claim 46 wherein the laser beam has a fluence in a range of 100 millijoules per square centimeter to 100 joules per square centimeter.

55. The method according to claim 46 wherein the laser beam defines a spot in or on the material and the LIB causes ablation of an area having a size smaller than the area of the spot.
56. The method according to claim 46 wherein the laser beam has a wavelength in a range of 200 nanometers to 2 microns.
57. The method according to claim 46 wherein the pulse width is in a range of a few picoseconds to femtoseconds.
58. The method according to claim 46 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.
59. The method according to claim 46 wherein the breakdown includes plasma formation.
60. The method according to claim 46 wherein the breakdown includes disintegration.
61. The method according to claim 46 wherein the breakdown includes ablation.
62. The method according to claim 46 wherein the breakdown includes vaporization.
63. The method according to claim 46 wherein the spot size is varied by flexible diaphragm to a range of 1 to 100 microns.
64. The method according to claim 46 wherein a mask is placed in the path of the beam to block a portion of the beam to cause the beam to assume a desired geometric configuration.
65. The method according to claim 46 wherein the laser operating mode is non-TEM<sub>00</sub>.



- b. focusing the laser beam initial start point at or beneath the surface of the material; and
- c. scanning said beam along a predetermined path in a transverse direction.

71. The method according to claim 69 and further including:

- a. identifying a pulse width start point;
- b. focusing the laser beam initial start point above the surface of the material; and
- c. scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the Rayleigh ange.

72. The method according to claim 69 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.

73. The method according to claim 69 wherein the breakdown includes plasma formation.

74. The method according to claim 69 wherein the breakdown includes disintegration.

75. The method according to claim 69 wherein the breakdown includes ablation.

76. The method according to claim 69 wherein the breakdown includes vaporization.

77. The method according to any one of claims 46, 47, 50 or 61 wherein said beam is obtained by chirped-pulse amplification (CPA) means comprising means for generating a short optical pulse having a predetermined duration; means for stretching such optical pulse in time; means for amplifying such time-stretched optical pulse including solid state amplifying media; and means for recompressing such amplified pulse to its original duration.

78. A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a predetermined laser pulse width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said predetermined laser pulse width; and

b. focusing said beam to a region of least confusion above the surface of the material so that the laser beam defines a spot and has a lateral gaussian profile characterized in that fluence at or near the center of the beam spot is greater than the threshold fluence whereby the laser induced breakdown is ablation of an area within the spot.

79. The method according to claim 78 wherein the spot size is a diffraction limited spot size providing an ablation cavity having a diameter less than the fundamental wavelength size.

80. A method for laser induced breakdown (LIB) of a material with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a rapid and distinct change in slope at a predetermined laser pulse width where the onset of plasma induced breakdown occurs, said method comprising the steps of:

a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said predetermined laser pulse width; and

b. focusing said beam to a region of least confusion above the surface of the material which is biological tissue, the pulse width is 10 to 10,000 femtoseconds and the beam has an energy of 10 nanojoules to 1 millijoule.

81. A method for laser Induced breakdown (LIB) of a material by plasma formation with a pulsed laser beam, the material being characterized by a relationship of fluence breakdown threshold versus laser pulse width that exhibits a distinct change in slope at a characteristic laser pulse width, said method comprising the steps of:

- a. generating a beam of one or more laser pulses in which each pulse has a pulse width equal to or less than said characteristic laser pulse width, said characteristic pulse width being defined by the ablation (LIB) threshold of the material as a function of pulse width where the ablation (LIB) threshold function is no longer proportional to the square root of pulse width; and
- b. focusing said beam to a region of least confusion above the surface of the material and inducing breakdown by plasma formation in the material.

82. A method for laser induced breakdown of a material which comprises:

- a. determining, for a selected material, a characteristic curve of fluence breakdown threshold ( $F_{th}$ ) as a function of laser pulse width;
- b. identifying a pulse width value on said curve corresponding to a rapid and distinct change in slope of said  $F_{th}$  versus pulse width curve characteristic of said material;
- c. generating a beam of one or more laser pulses, said having a pulse width at or below said pulse width value corresponding to said distinct change in slope; and
- d. focusing said one or more pulses of said beam to a region of least confusion above the surface of the material.

83. The method according to claim 82 and further including:

- a. identifying a pulse width start point;
- b. focusing the laser beam initial start point at or beneath the surface of the material; and
- c. scanning said beam along a predetermined path in a transverse direction.

84. The method according to claim 82 and further including:

- a. identifying a pulse width start point;
- b. focusing the laser beam initial start region of least confusion above the surface of the material; and
- c. scanning said beam along a predetermined path in a longitudinal direction in the material to a depth smaller than the Rayleigh range.

85. The method according to claim 40 wherein the breakdown includes changes caused by one or more of ionization, free electron multiplication, dielectric breakdown, plasma formation, and vaporization.

86. The method according to claim 82 wherein the breakdown includes plasma formation.

87. The method according to claim 82 wherein the breakdown includes disintegration.

88. The method according to claim 82 wherein the breakdown include ablation.

89. The method according to claim 82 wherein breakdown includes vaporization.

90. The method according to any one of claims 80 or 82 wherein said beam is obtained by chirped-pulse amplification (CPA) means comprising means for generating a short optical pulse

having a predetermined duration; means for stretching such optical pulse in time; means for amplifying such time-stretched optical pulse including solid state amplifying media; and means for recompressing such amplified pulse to its original duration.

91. A method according to claims 1, 7, 24, 33, 35, 36, 37, 38, 46, 52, 69, 78, 80, 81, 82 or 83 wherein said material is disposed on another material.

92. A method according to claim 91 wherein said another material is the same as said material.

93. A method according to claim 91 wherein said another material is different than said material.

94. A method according to claims 1, 7, 24, 33, 35, 36, 37 or 38 wherein said laser-induced breakdown removes said material from said surface resulting in an ablated surface.

95. A method according to claim 95 wherein said point is moved as said material is removed from said surface so that said point is substantially maintained at a fixed distance above said ablated surface.

96. A method according to claim 46, 52, 69, 78, 80, 81, 82 or 83 wherein said laser-induced breakdown removes said material from said surface resulting in an ablated surface.

97. A method according to claim 96 wherein said region of least confusion is moved as said material is ablated so that said region of least confusion is substantially maintained at a fixed distance above said ablated surface.

98. A method according to claim 91 wherein said another material is a first tissue and said material is a second tissue.

99. A method according to claim 98 wherein said first tissue is a tumor and wherein said second material is normal tissue.



100. A method according to claim 99 wherein said second tissue is a retina of an eye and said tumor is disposed on said retina.

100. A method according to claim 99 wherein said second tissue is a retina of an eye and said tumor is disposed on said retina.